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Extragalactic γ-rays [and Discussion]

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Extragalactic γ-rays

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Only a few extragalactic objects have been studied in the γ-ray region of the spectrum. At high energies the COS-B experiment detected emission from the quasar 3C273 while at lower energies the results indicate that the emission from the Seyfert galaxy NGC 4151 is variable. A similar variability may also account for the conflicting reports of line emission from the radio galaxy Cen A. The implication of these and other observations in relation to the possible physical conditions in the nuclei of active galaxies.

1. Introduction

Although there exists a variety of interesting extragalactic objects that are highly luminous in other wavelengths, very few observational data have been gathered in the γ-ray region of the spectrum. In several cases, which are discussed below, an important part of the picture that describes the properties of these objects is uncertain because of the paucity of results obtained, so far, above 200 keV. It is interesting that γ-radiation has been detected from a quasar (3C273), a Seyfert galaxy (NGC 4151) and a radio galaxy (Cen A). However, these objects are all relatively nearby examples of their respective classes and hence a positive measurement is especially favoured.

The reasons for this lack of data are not difficult to find. The observation time of both the SAS-2 and COS-B high energy γ-ray astronomy experiments was largely devoted to the search for the diffuse galactic component and that from point sources along the galactic plane. As a consequence, large areas of the sky have not been explored by COS-B in the search for γ-ray sources; these are shown by the shaded regions in figure 1 (Swanenburg *et al.* 1980). This figure also shows the locations of those γ-ray sources that have been detected above 100 MeV and indicates how closely concentrated most of these are along the galactic plane. In the region $360° < l < 60°$, the average deviation from $b = 0°$ is 1.1°. Those sources significantly displaced from the plane include 2CG289+64 which has almost certainly been linked with the quasar 3C273 (Swanenburg *et al.* 1978), 2CG353+16 which is located in the ρ-Oph cloud complex (Mayer-Hasselwander *et al.* 1980) and, thirdly, the unidentified source 2CG010−31. Parts of the COS-B data relating to those periods when the instrument was pointed away from the galactic plane have been studied in more detail to search for possible emission from a range of specific extragalactic objects which included Seyfert galaxies, quasars, BL Lac objects and other active galaxies (Pollock *et al.* 1981). With the exception of 3C273, upper limits of *ca.* 2×10^{-6} ph cm^{-2} s^{-1} were set for a range of objects within the regions of sky that were studied. The small area of sky covered by this specific search for extragalactic objects by the likelihood method is shown in figure 2. This survey reinforced the general conclusions of Bignami *et al.* (1979), that the spectra of active galaxies steepens significantly between the X-ray and the high γ-ray regions of the spectrum.

The γ-ray luminosity of our own Galaxy has been estimated by Strong & Worrall (1976) to be close to 5×10^{38} erg s^{-1}† (above 100 MeV) and may be used to calculate the probable flux from other similar spiral galaxies. For example, the flux that one might expect from M31 is about one-tenth the upper limits set by the COS-B search for extragalactic objects. Even if a significant proportion of time were to be devoted by the proposed, more sensitive, GRO track-chamber telescope, other normal galaxies would, at best, be barely detectable.

At low γ-ray energies there is similar bias in the data currently available. In this case the range of sources observed is even more limited because of the nature of the balloon-borne

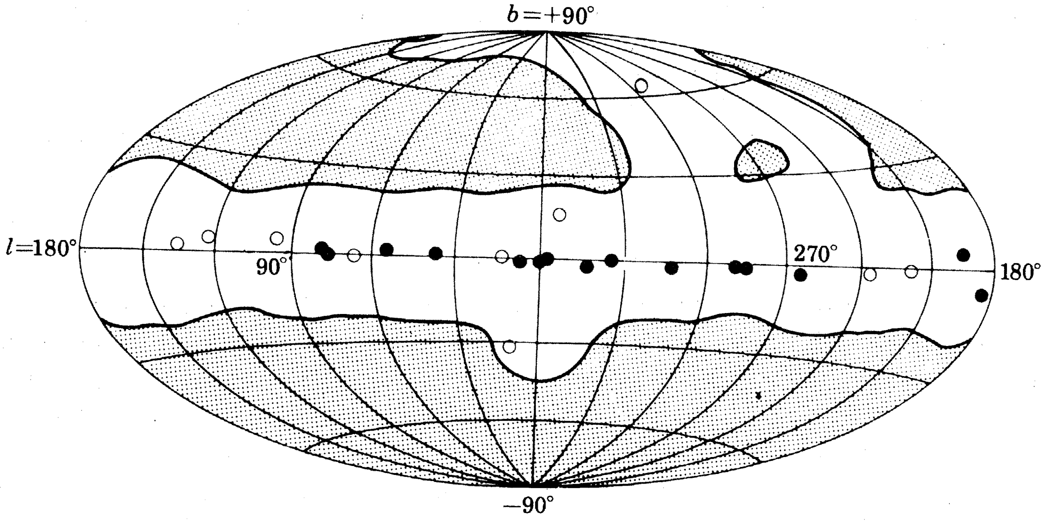

FIGURE 1. Region of the sky searched by COS-B for γ-ray sources (unshaded), and sources detected above 100 MeV by spatial analysis. The closed circles denote sources with measured fluxes above 1.3×10^{-6} ph cm^{-2} s^{-1}. Open circles denote sources below this threshold.

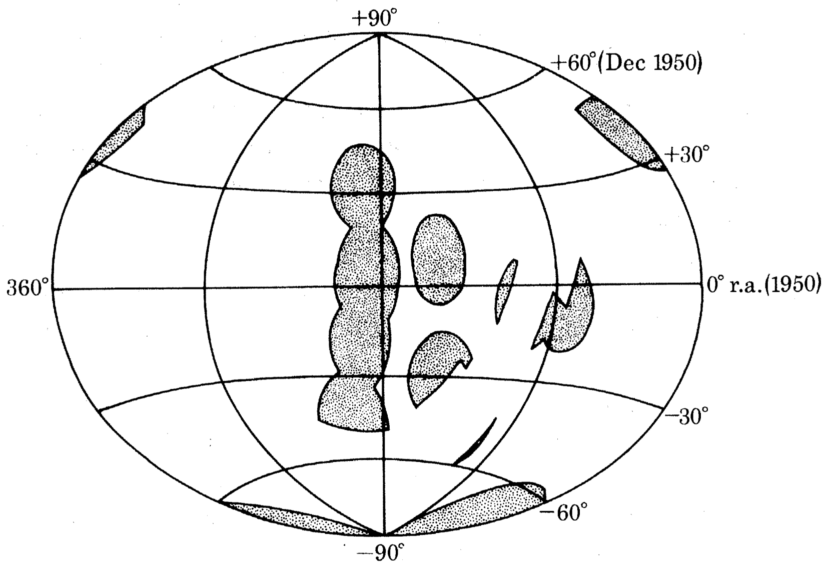

FIGURE 2. The areas of the sky used in the COS-B search for γ-ray emission from extragalactic objects are shown as shaded regions.

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† 1 erg s^{-1} = 10^{-7} W.

instruments and the location of the balloon launching sites used. Two broad types of telescope have been used in this field. The Rice group (Meegan & Haymes 1979) and the MISO collaboration (Baker *et al.* 1979), have used collimated detectors to define the region of sky to be studied, while U.C.R. (Herzo *et al.* 1975) and M.P.I. (Graml *et al.* 1978) have used multi-element Compton time-of-flight telescopes to define the direction of origin of a photon within a large acceptance angle. Although some observations have been made in the Southern Hemisphere there has been an emphasis on Northern-Hemisphere sources for practical reasons related to the fact that good balloon facilities are provided at Palestine, Texas (32 °N).

However, the HEAO-A4 experiment was designed to survey a large fraction of the sky in the energy range 80–2300 keV and one hopes that results from this more comprehensive study will be available soon. Some of their preliminary results have indicated that the emission from Cen A in fact peaks at low γ-ray energies. A more sensitive survey should be available when GRO is operational.

In view of the very small number of extragalactic objects that have been detected so far at γ-ray energies and the fact that the emission from non-active galaxies is below the level of sensitivity of currently available telescopes, the following discussion centres on the mechanisms for the production of γ-rays in the nuclei of active galaxies.

2. Seyfert galaxies and γ-ray emission

(*a*) *General properties of Seyferts*

The Seyfert class of galaxies was first discovered in 1943 (Seyfert 1943), and may be defined as those with an optically compact nucleus that emits intense broad emission lines (Weedman 1977). Seyferts are traditionally subdivided into two classes on the basis of the relative width of the allowed and forbidden lines. Type I Seyferts have broad Balmer lines for which the full-width zero-intensity indicates velocities of up to 20000 km s^{-1}, and narrow, but strong, forbidden lines. Type II Seyferts have narrow Balmer lines and weak, narrow forbidden lines. The gas distribution in the nuclei of type I Seyferts is probably very inhomogeneous since the forbidden lines are never seen to exhibit the broad wings seen on the permitted lines. The gas that is emitting the broadened lines may therefore be considered to be very dense ($N_e > 10^8$ cm^{-3}) so that the forbidden radiation is suppressed (Wilson 1979). The timescale of the variability of the Balmer lines (Tohline & Osterbrock 1976), and the inability to resolve any spatial structure in type I Seyferts, supports the conclusion that the permitted lines originate from a much smaller region of the nucleus than the forbidden lines. Conversely, observations of the forbidden lines in some nearby Seyfert galaxies (NGC 1068, NGC 4151, HGC 7409) have resolved distinct clouds with radii of typically a few parsecs (Walker 1968*a*, *b*; Ulrich 1972).

The non-thermal optical emission may be considered as coming from a compact region (0.1 pc) since it varies in intensity over a period of about one month (Penston *et al.* 1974). From this optical information, we may obtain the simplified picture of a compact (0.1 pc), high density non-thermal core ($N_e > 7 \times 10^8$ cm^{-3}) with high velocity dispersion (*ca.* 10^4 km s^{-1}), and a low density region $N_e \approx 10^3$ cm^{-3}.

More variety is exhibited in Seyfert galaxies at centimetric radio wavelengths, and Wilson (1979) has divided them into four categories:

(i) Powerful (above 10^{25} W Hz^{-1} sr^{-1}) extended double sources with steep spectra. Sometimes a third, weaker, radio source is associated with the galactic nucleus.

(ii) Powerful (below 10^{24} W Hz^{-1} sr^{-1}) compact (1–3 pc) radio sources. The spectra for these are flat with a power-law exponent $\alpha \approx 0$. The spectra often show multi-component characteristics indicative of synchrotron self-absorption.

(iii) Weaker (10^{20} to 10^{23} W Hz^{-1} sr^{-1}) emission from the galactic nuclei. Generally these have steep power-law spectra and sometimes exhibit a very extended (50 kpc) radio halo.

(iv) No detected radio emission.

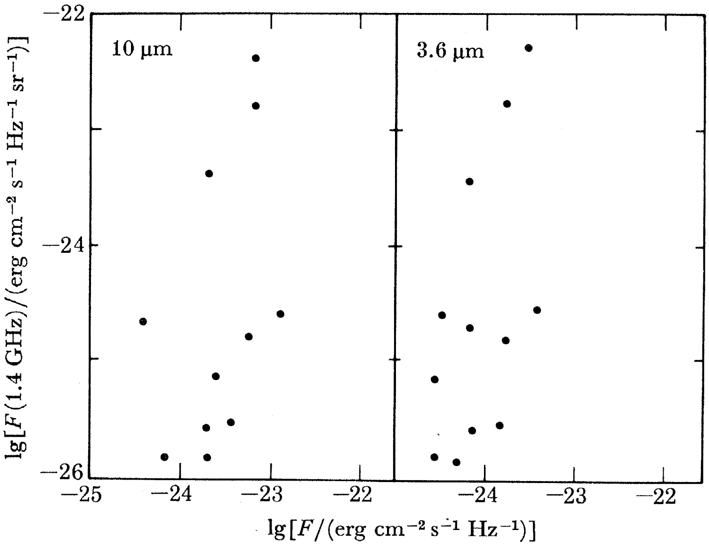

FIGURE 3. Infrared fluxes at 3.6 μm and 10 μm plotted against radio flux at 1.4 GHz.

Most of the Seyfert galaxies (*ca.* 90%), as classified by optical observations (Weedman 1977), fall into classifications (iii) and (iv), and the energy radiated at radio wavelengths (10^{38} to 10^{40} erg s^{-1}) is negligible compared with the infrared and X-ray emissions. There appears to be a correlation between continuum radio emission and type II Seyferts (see, for example, a survey by De Bruyn & Wilson 1976). In Seyfert galaxies it would appear that the intensity of the radio emission is related to that of the forbidden line luminosity.

Studies of Seyfert galaxies at infrared wavelengths have shown differences between the emission from type I and type II Seyferts (Stein & Wedman 1976, Neugebauer *et al.* 1976). Both types, however, emit a significant fraction of their total luminosity (10^{42} to 10^{45} erg s^{-1}) in the infrared region of the spectrum (Rieke & Low 1972, Penston *et al.* 1974). It is probable that three components contribute to the total i.r. emission: a galactic stellar component, a thermal component from heated dust grains, and a non-thermal component. It appears that in type I Seyferts the non-thermal mechanism dominates, while in type II, thermal radiation from the heated dust is most important since neither the Balmer lines nor the continuum are significantly reddened (Stein & Weedman 1976). Neugebauer *et al.* (1976) and McAlary *et al.* (1979) found that the continuum spectra of type II Seyferts that they observed were best described by a combination of stellar and dust radiation. It is also thought that the steep Balmer decrements of the type II objects are a consequence of the reddening by dust. A weak correlation has been found between the 10 μm and 3.6 μm infrared emission and the 1.4 GHz radio flux for both type I and type II Seyferts (De Bruyn & Wilson 1976, Rieke 1978); this is shown in figure 3. This suggests that the dust responsible for the thermal component at the longer infrared wavelengths may be located in the same region as the radio emission. At least in one case, NGC 4151, observation supports the presence of dust in the forbidden line region (Schmidt & Miller 1980).

Table 1. List of X-ray Seyferts

name	type	L(2–10 keV)/(erg s^{-1})
III Zw2	1	1.4×10^{45}
MKN 335	1	7.8×10^{43}
NGC 1275	?	2.3×10^{44}
AKN 120	1	3.1×10^{43}
MCG 8-11-11	1	8.5×10^{43}
MKN 79	1.2	6.3×10^{43}
NGC 3227	1.2	6.3×10^{43}
MKN 40	1	6.0×10^{43}
NGC 3783	1	1.9×10^{43}
NGC 4151	1.5	7.1×10^{42}
IC 4329A	1	7.1×10^{43}
MkN 279	1	1.7×10^{44}
NGC 5548	1.5	5.6×10^{43}
ESO 141-655	1	1.1×10^{44}
NGC 6814	1	4.3×10^{42}
MKN 509	1	2.5×10^{44}
MKN 304	1	6.4×10^{44}
NGC 7469	1	6.3×10^{43}
MCG 2-58-22	1	3.3×10^{44}
MKN 541	1	8.3×10^{43}
3C 120	1	2.2×10^{44}
MKN 376	1	3.8×10^{44}
ESO 113 IG 45	1	2.2×10^{44}
NGC 4593	1	2.9×10^{42}
NGC 2110	2	2.9×10^{42}
NGC 931	1	1.6×10^{43}
MKN 464	1	8.5×10^{43}
MKN 876	1	9.8×10^{44}
3C 382	1	4.6×10^{44}
NGC 7213	1	2.9×10^{42}
3C 390.3	1	4.9×10^{44}

There is a strong tendency for X-ray emission (2–10 keV) to be detected from type I Seyfert galaxies (Elvis *et al.* 1978). The exceptions, NGC 1275 for example, are normally classified as peculiar. The lack of correlation with type II Seyfert galaxies is not due to a distance effect since they are, on average, nearer than type I Seyferts. For the 71 type I Seyfert galaxies in Weedman's (1977) list after some reclassification has been allowed for, the average recession velocity is 14000 km s^{-1}, while for the 16 type II Seyferts the velocity is 7000 km s^{-1}. Since only the type I Seyferts have a 'core' region from which the broad wings of the permitted lines and the non-thermal infrared emission are believed to originate, one is tempted to associate the X-ray emission with this 'core' region, which is peculiar to type I Seyferts. The fact that the X-ray emission is well represented by power-law spectra (Mushotzky *et al.* 1980) strengthens this belief. This association is further strengthened by the short timescale of the X-ray variability that has been found in several Seyferts (Elvis 1976; Ward *et al.* 1977; Mushotzky & Marshall 1980; Mushotzky *et al.* 1980). The X-ray region of such Seyferts as NGC 4151, MCG 8–11–11, MKN 509 and NGC 3783 cannot be greater than 0.01 pc and is possibly considerably smaller. It is interesting to note that whereas type I Seyferts correlate strongly with X-ray emission the results of similar radio studies show a preference for type II. A list of X-ray Seyferts is given in table 1. The X-ray luminosity of Seyfert galaxies is seen to be high, 10^{42} to 10^{45} erg s^{-1}.

(*b*) *The correlation between the X-ray flux and emission at other wavelengths*

Type I Seyfert galaxies that are found to be X-ray emitters also tend to be the brightest in the optical region of the spectrum.

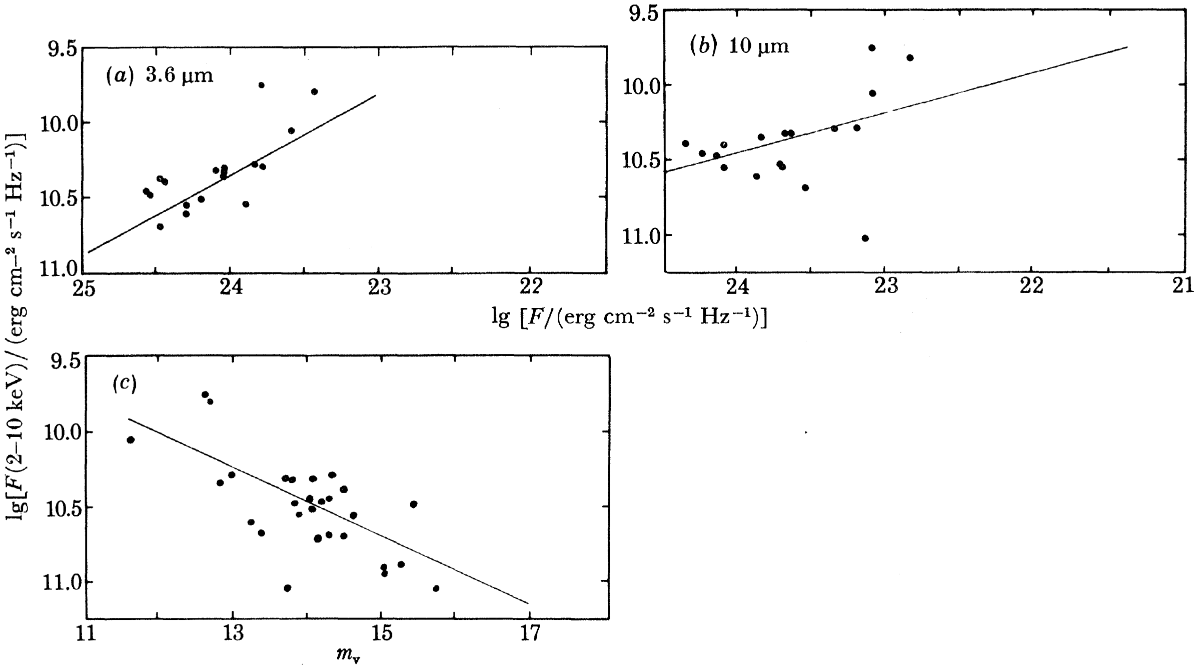

FIGURE 4. X-ray flux (2–10 keV) plotted against infrared fluxes (3.6 μm and 10 μm) and visual magnitude, m_v.

In figure 4 the 2–10 keV flux density has been plotted as a function of the radio, infrared and optical emission strength. Whereas the correlation with radio fluxes is very weak, there is a strong correlation with infrared emission at 10 μm and 3.6 μm. A strong correlation also exists between the X-ray emission and the strength of the optical continuum as well as the full-width zero-intensity of the Balmer lines. Little, or no, correlation exists between X-ray luminosity and forbidden line emission. The fact that the significant correlation with the X-ray luminosity derives from properties associated with the 'core' region further strengthens the argument that the X-ray emission originates within the central core itself.

So far, there have been only a few measurements of Seyfert galaxies at γ-ray wavelengths. Bignami *et al.* (1979) give a list of the 95% confidence upper limits for several Seyfert galaxies studied by the SAS-2 spark chamber telescope in the energy band 35–100 MeV and above 100 MeV. Similarly the COS-B γ-ray telescope has failed to identify, positively, any Seyfert galaxy as a γ-ray emitter above about 50 MeV (Pollock *et al.* 1981). Only NGC 4151 has been positively identified as a γ-ray source in the 0.2–5 MeV region of the spectrum (Di Cocco *et al.* 1977, Perotti *et al.* 1979), and as a hard X-ray emitter up to at least 0.2 MeV by two research groups (Auriemma *et al.* 1978, Paciesas *et al.* 1977). Both the low energy γ-ray measurements and the high energy γ-ray upper limits imply that a change in spectral slope must occur between X-ray and high energy γ-ray energies. The upper limits derived from the SAS–2 γ-ray data also provide evidence that changes in the spectral slope must take place in other Seyfert galaxies since the upper limits are substantially below the extrapolation of their X-ray power-law spectra. A steepening in the spectra between X-ray and γ-ray energies may therefore be a general characteristic of Seyfert galaxies.

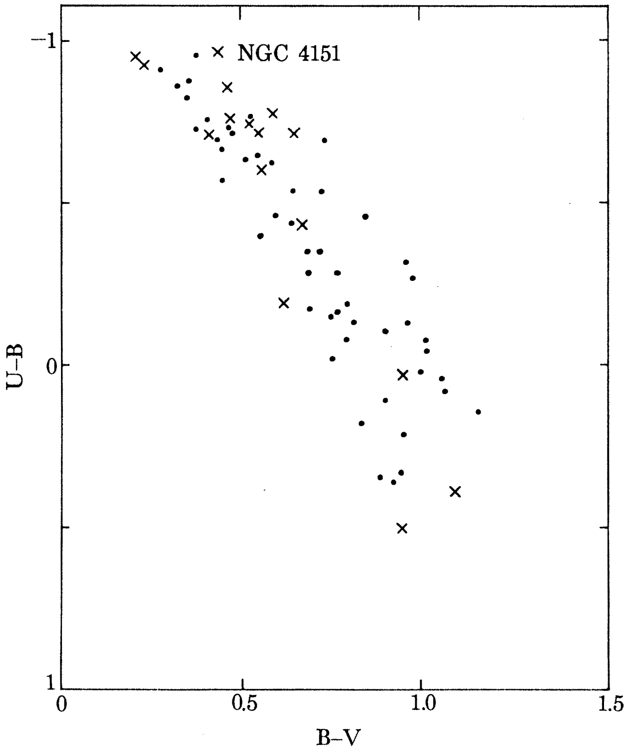

FIGURE 5. Colour–colour plot for the nuclei of a number of Seyfert galaxies (Weedman 1977). ×, Known X-ray sources; •, not known as X-ray sources.

(c) *The galaxy NGC* 4151

Currently NGC 4151 is not only the best studied Seyfert galaxy at γ-ray wavelengths but has also been thoroughly investigated at all wavelengths available to the astronomer for many years. To attempt to understand the relevance of γ-ray astronomy to the understanding of Seyfert galaxies and active galaxies in general, it is appropriate to review briefly the data available on this object. NGC 4151 is frequently taken to be the archetype of type I, X-ray-emitting Seyferts, but in fact the Balmer profiles show sharp components superimposed on broad, weak, components and this galaxy may be better classified as type 1.5. Furthermore, it is one of the nearest (19 Mpc, $H_0 = 50$ km Mpc^{-1}) and intrinsically the weakest of that class (L_X(2–10 keV) $= 7.1 \times 10^{42}$ erg s^{-1}). The colour–colour plot for the nuclei of various Seyferts (figure 5) indicates that NGC 4151 may not be entirely typical, a point to be remembered in any generalization about contributions to the diffuse γ-ray flux from Seyfert galaxies on the basis of the NGC 4151 observations

The spectrum of NGC 4151 from radio to γ-ray frequencies is shown in figure 6. Most components of the spectrum seem to be characterized by non-thermal emissions and a high degree of variability in the infrared, optical, ultraviolet and X-ray regions of the spectrum (Lebofsky *et al.* 1980, Lyutyi 1977, Boksenberg *et al.* 1980, Lawrence 1980). The simplest explanation for the variations in all spectral regions would be that a single, non-thermal, source dominates the output of this galaxy over the entire wavelength range. However, the variations are not simultaneous but have widely differing time constants and sometimes occur in opposite senses in the different spectral regions. The variability is characterized by both rapid and slow changes at different wavelengths. Figure 7 shows the i.r. variability of NGC 4151 over several years, along with that of some other Seyferts. The steeply rising i.r. spectrum of NGC 4151 suggests that re-radiation by dust lying *ca.* 0.6 pc from the non-thermal source is an important component of its spectrum. Such a model explains the slower i.r. variations and the apparent delay with respect to u.v. fluctuations. The optical light curve, taken from Lyutyi (1977), is shown in figure 8. At least two components can be distinguished: a rapid flare component, with a characteristic variability timescale of ten days, and a slow component which varies typically on a timescale of a few years. The slow component is distinctly cyclic with a period of about 3–4 years. Photoelectric observations of NGC 4151 by Cherepashchuk & Lyutyi (1973) show variations in H_α intensity over a timescale of 5–10 days. These H_α and other line feature variations follow the variations seen in optical continuum but with a time lag of about 30 days in 1970–72 which increased to about 70 days by 1976. The authors interpret this delay as due to the time taken by the ionizing particles to travel from the central source. Thus the

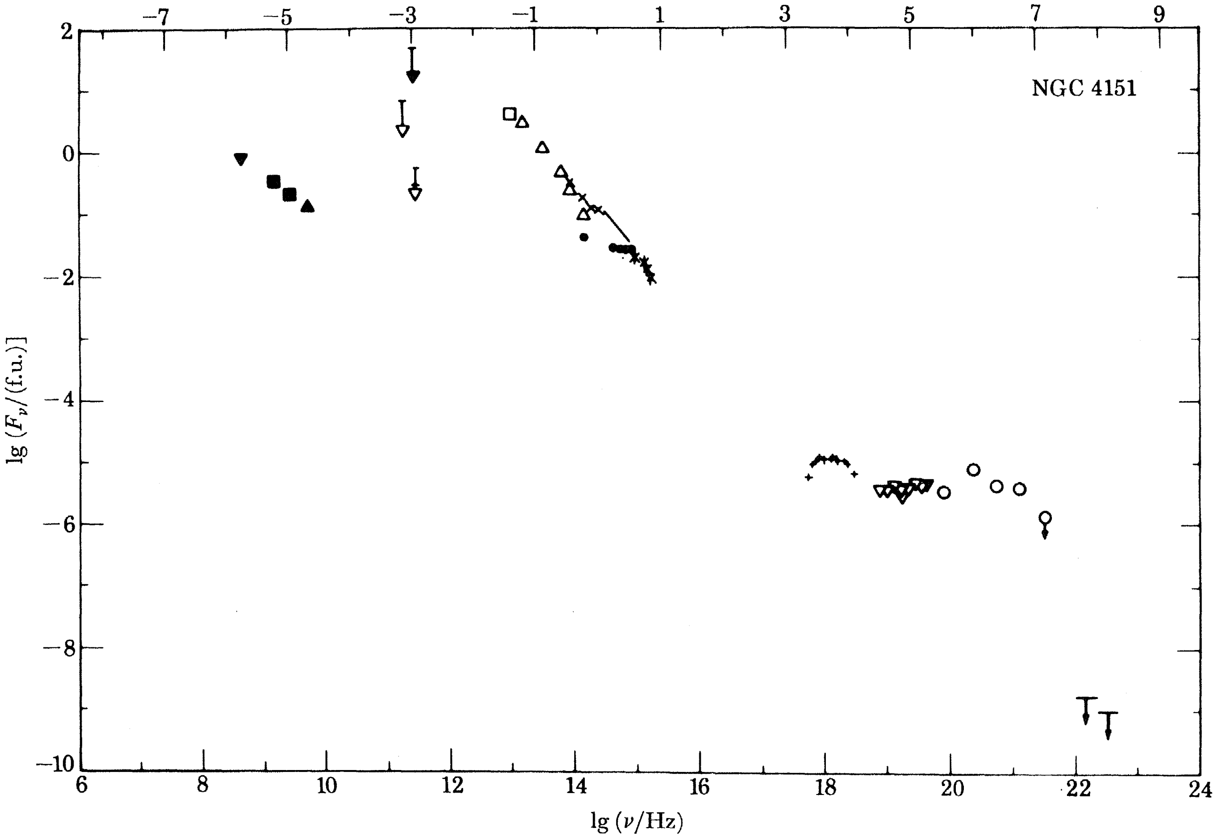

FIGURE 6. Composite spectrum of NGC 4151 (after Schlickeiser 1980*b*).

optical data again present us with a picture of a central source, perhaps 10^{16} cm in size, feeding energy to a large region (10^{17} cm) from which the variable H_α emission arises. Observations of NGC 4151 with the I.U.E. satellite (Boksenberg *et al.* 1980), have confirmed that the u.v. emission, in both the continuum and emission lines, varies by a factor of two in about two weeks. It is interesting to note that the u.v. variations do not follow the same pattern as the variations observed at 10 keV by the Ariel 5 satellite.

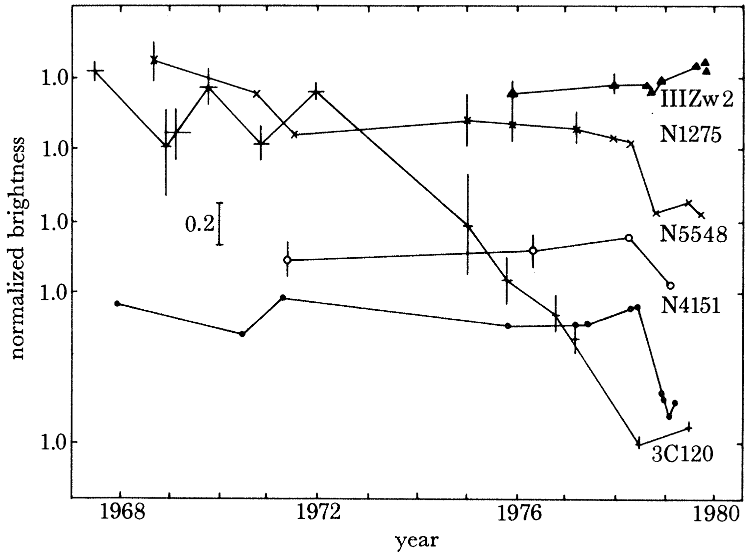

FIGURE 7. Infrared variability of NGC 4151 and a selection of other Seyfert galaxies.

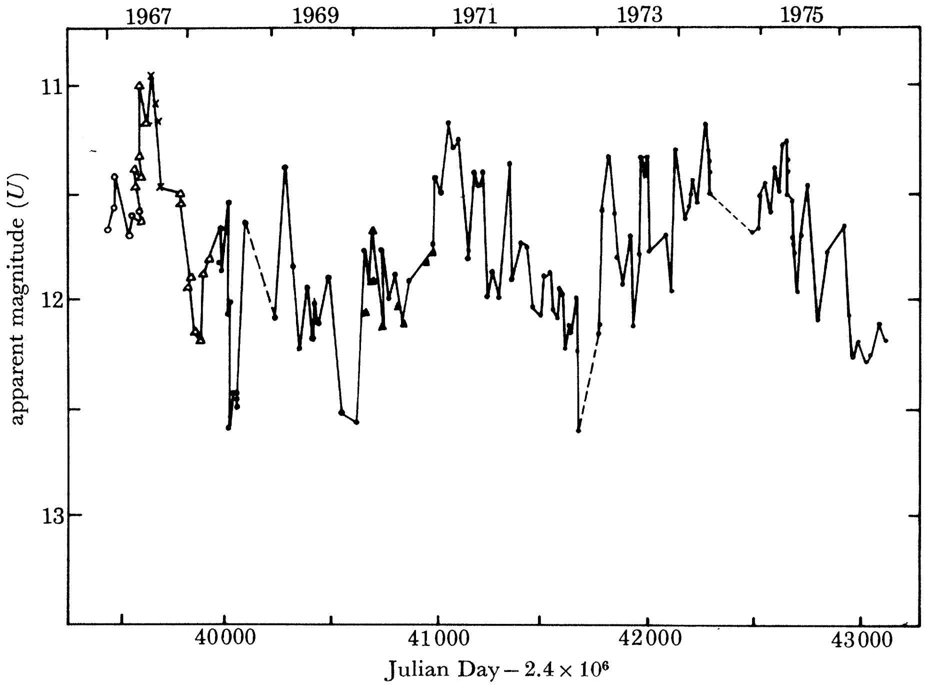

FIGURE 8. Optical variability of NGC 4151.

(*d*) *X- and γ-ray observations of NGC* 4151

The X-ray source in NGC 4151 has been extensively studied at X-ray wavelengths by Uhuru (Ulmer 1977), Ariel 5 (Ives *et al.* 1976), the U.C.S.D. detector (Paciesas *et al.* 1977), the U.C.S.D. OSO-7 experiment (Baity *et al.* 1975), OSO-8 (Mushotzky *et al.* 1978*a*), the experiments on HEAO-1 (Mushotzky *et al.* 1980, Baity *et al.* 1979) and by the Frascati group (Auriemma *et al.* 1978) and the Bologna X-ray telescope (Frontera *et al.* 1979). The data indicate that the X-ray spectrum is best represented by a power law with a low energy cut-off near 2–5 keV. If the spectrum is represented by

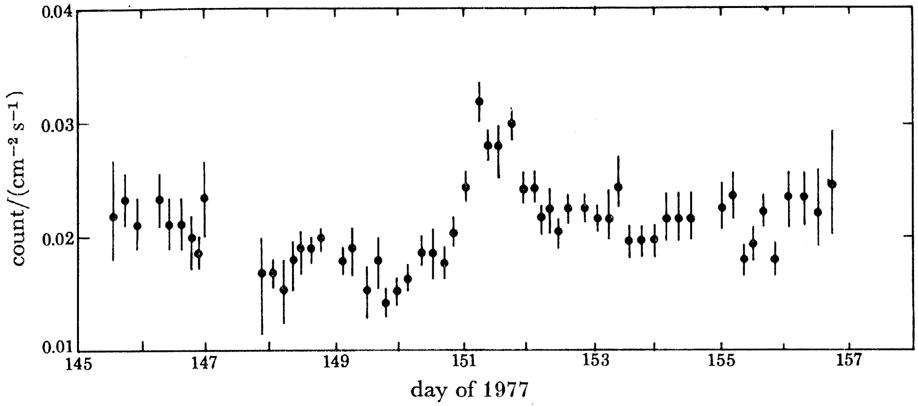

FIGURE 9. X-ray (2–60 keV) flare observed in NGC 4151 by OSO-8 during May 1977.

$$\mathrm{d}N/\mathrm{d}t = AE^{-\alpha}\exp(-N_{\mathrm{H}}\sigma),$$

where σ is the absolute cross section, then the quoted parameters α and N_{H} derived from the observations are as summarized below.

	α	$N_{\mathrm{H}}/\mathrm{cm}^{-2}$
Uhuru	-1.1	
Ariel 5	1.62 ± 0.2	4.2×10^{22} (Nov 1974)
	1.39 ± 0.2	5.2×10^{22} (Jan 1976)
OSO-7	1.1 ± 0.2	
OSO-8	1.49 ± 0.06	$7.5 \pm 0.5 \times 10^{22}$
HEAO-1 A2	1.43 ± 0.08	$1.0 \pm 0.2 \times 10^{23}$
HEAO-1 A4	1.4	
Frascati	0.9 ± 0.2	

The average X-ray luminosity (2–10 keV) of NGC 4151 is 7.1×10^{42} erg s^{-1} which makes this object one of the weaker Seyfert X-ray sources. The X-ray emission from NGC 4151 is undoubtedly variable. Tananbaum *et al.* (1978), using Uhuru data, have suggested that intense activity on a timescale of 700 s occurs. Observations with the Ariel 5 satellite (Ives *et al.* 1976, Barr *et al.* 1977), which were taken several months apart, showed the low energy cut-off to be very variable. No change was seen in the spectral index or intensity and it was concluded that the broad-band variability was explained by changes in the column density of matter between us and the X-ray source. However, the measurements of Mushotzky *et al.* (1978*a*) revealed very significant flare activity (figure 9) with no corresponding changes in spectral index or column densities. The flare reported by that group was of the saw-tooth variety, had a rise time of about 1.5 days and decayed over a period 3–4 days. The Ariel 5 satellite observed NGC 4151 regularly throughout its four year lifetime. Lawrence (1980) has presented a detailed analysis of these data and has revealed that flaring on a timescale of days has occurred frequently in NGC 4151 throughout the four year period. Some typical data taken from the Ariel 5 observations are shown in figure 10. Lawrence (1980) goes so far as to propose that all the X-ray emission from this galaxy arises in flare-like events, and he presents the analysis of the data in terms of a shot-noise model. He concludes that the 2–10 keV X-ray emission from NGC 4151 varies continuously by a factor of two. Saw-tooth flares with rise times of 0.5 days, or less, and decay times of 1–2 days are very common. We may presume therefore that the X-ray source has dimensions of typically 10^{14} cm or less.

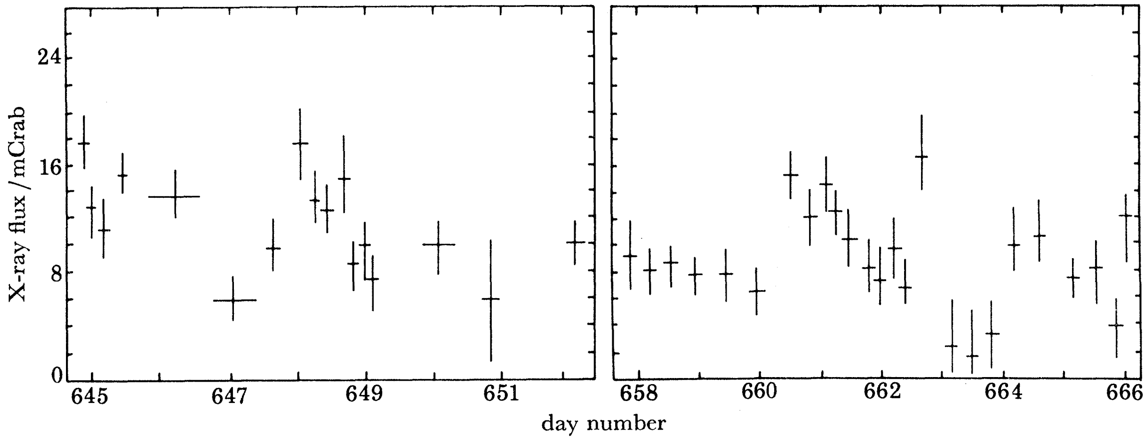

Figure 10. X-ray (2–10 keV) flare activity observed by Ariel 5.

NGC 4151 has been observed several times in the low energy γ-ray region of the electromagnetic spectrum. Those observations that have been reported are in May 1977 by the MISO experiment (Di Cocco *et al.* 1977, Perotti *et al.* 1979), October 1977 (Graml *et al.* 1978, Meegan *et al.* 1979), and September 1978 (White *et al.* 1980). The results of Graml *et al.* (1978) were subsequently withdrawn at the International Cosmic Ray Conference in Kyoto, August 1979. With the exception of Perotti *et al.* (1979) the γ-ray observations at 1 MeV may be represented by upper limits. NGC 4151 passed through the aperture of the U.C.R. telescope twice in about 24 h and in each case there was no evidence for any excess flux. Analysis of the data from the Rice scintillation counter telescope enabled a series of upper limits to be set on the spectral intensity in the energy range from about 100 keV to 8.7 MeV. In the energy range 116 keV to 172 keV their data set an upper limit that is inconsistent with the data of Auriemma *et al.* (1978) at the 99.9% confidence level (3.4σ) and lies considerably below the flux measured by the MISO telescope. The full analysis of the MISO data from the observation of this Seyfert galaxy (Perotti *et al.* 1979) shows that the excess count rate originates from within 20′ of NGC 4151 and is consistent with the 3° f.w.h.m. collimator profile of this instrument (figure 11). The spectral data show evidence for a break close to 3 MeV and may be described as either a combination of two power laws ($\alpha = 0.9$ up to 3 MeV; $\alpha = 3.4$ above 3 MeV) which gives a reduced $\chi^2 = 0.73$ with 19 degrees of freedom or, alternatively, the measurements may be represented for energies greater than 200 keV by an exponential of the form

$$\mathrm{d}I/\mathrm{d}E = (1.6 \pm 0.7) \times 10^{-5} \exp[-E/(2120 \pm 480)] \quad [\mathrm{ph\ cm^{-2}\ s^{-1}\ keV^{-1}}]$$

The corresponding reduced χ^2-value is 0.5 for three degrees of freedom. Figure 12 shows the X- and γ-ray spectra and also includes the upper-limit values above about 30 MeV taken from the SAS-2 satellite. The upper limits on NGC 4151 for photon energies greater than 50 MeV recently reported by the COS-B collaboration (Pollock *et al.* 1981) do not significantly change the picture.

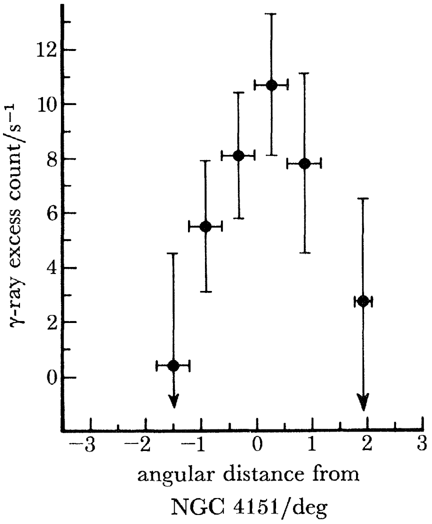

FIGURE 11. Gamma-ray excess as a function of angular offset from direction of NGC 4151.

3. OTHER X- AND γ-RAY ACTIVE GALAXIES

A substantial number of Seyfert galaxies have been detected as X-ray sources and may therefore be considered as prime candidates for potential γ-ray emitters. However, other classes of active galaxies have also been identified as X-ray emitters (two of which, Cen A and 3C273, are proven γ-ray sources) and must therefore also be considered as potential γ-ray sources. In this section we do not specifically discuss the observational data at other wavelengths but instead concentrate primarily on the X- and γ-ray measurements. For the sake of simplicity and because of the lack of γ-ray observational data, the discussion in this section centres around a so-called 'archetypal' example for each class of active galaxy.

(*a*) *Quasars*

Before the launch of the Einstein Observatory there were three known X-ray-emitting quasars: 3C273 (Bowyer *et al.* 1970); 2A2251–179 (Ricker *et al.* 1979); and 4U0241+61 (Apparao *et al.* 1978). Observations with the Einstein X-ray telescope (Tananbaum *et al.* 1979) have shown that quasars, as a class, are luminous X-ray emitters. Assuming that the optical emission-line redshifts give a valid indication of distance, the 0.5–4.5 keV X-ray luminosities lie in the range 10^{43} to 10^{47} erg s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$). Tananbaum *et al.* (1979) provide a table that lists the quasars that have been detected, in order of increasing redshifts. The observed fluxes are converted to luminosities over a fixed energy band, 0.5–4.5 keV at the source, by using the Friedman model. It should be noted that the luminosities are strongly dependent on the deceleration parameter q_0.

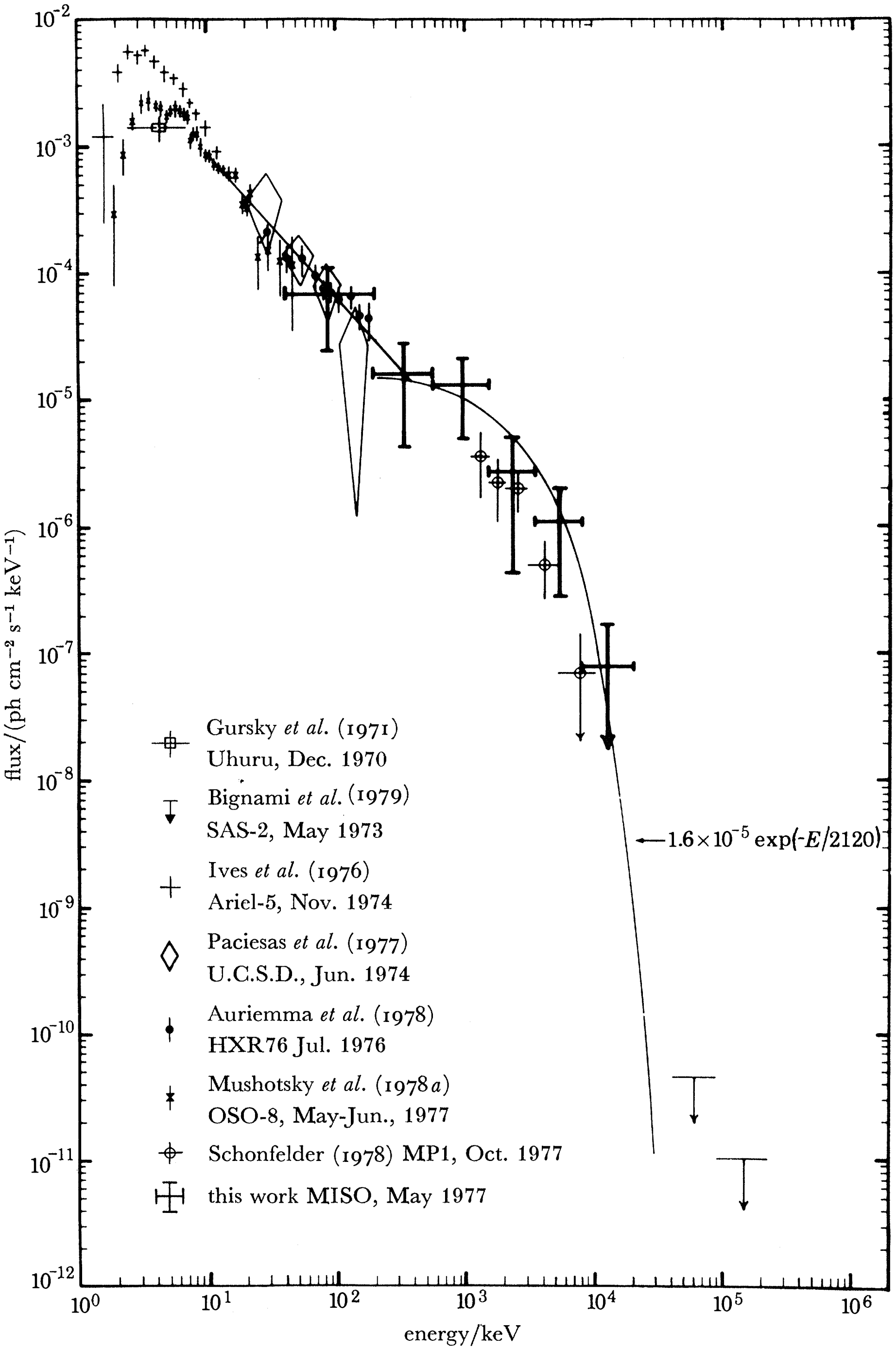

FIGURE 12. Spectrum of NGC 4151 in the range 1 keV to 1 GeV.

Studies are currently being made of the time-dependent flux from X-ray quasars and there is a strong indication of variability in some cases. For example, the quasar OX–169 has shown significant variability (threefold) on a timescale of more than about 10^4 s (Tananbaum *et al.* 1979). The X-ray luminosities of some other quasars are known to vary over a period of months. The study of several low redshift, radio-quiet quasars at optical wavelengths has shown a strong correlation between X-ray luminosity and both the continuum and broad-line (for example H_β) emission luminosities (Grindlay *et al.* 1980). This is shown in figure 13. The low-z objects had very similar mean values of $L_X/L_{opt} = 0.4$, but L_X varies by a factor of about 10. A similar correlation between L_β and L_X observed for Seyfert galaxies has been presented by Elvis *et al.* (1978). No such correlation between the emission line intensities and X-ray luminosities are found in radio bright quasars.

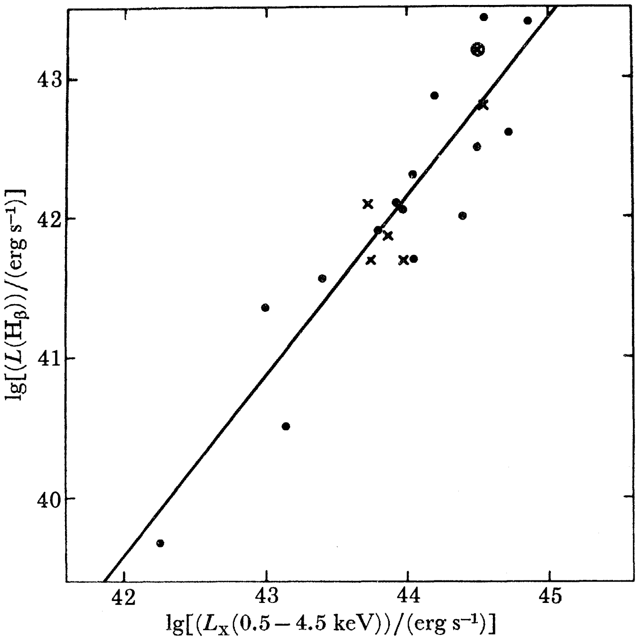

FIGURE 13. The X-ray luminosity of a sample of Seyfert galaxies and quasars plotted as a function of H_β luminosity. ×, X-ray selected quasars; •, Seyfert galaxies; ——, $\lg(L(H_\beta)) \approx -14.6 + 1.29 \lg L_X$.

The brightest quasar as viewed from the Earth is 3C273 which has a luminosity of $L_X = 1.7 \times 10^{46}$ erg s^{-1} in the 0.5–4.5 keV energy band. It is the only active galaxy that has been clearly identified as a source of γ-rays having energy above 100 MeV (Swanenberg *et al.* 1978). Bignami *et al.* (1981) quote the error box containing the quasar at the 90% confidence level as 2.5°. The measured differential photon spectrum is well fitted by the following power law:

$$dN/dE = (3.7 \pm 1.4) \times 10^{-6}[(E/\text{MeV})/150]^{-2.5} \quad [\text{ph cm}^{-2}\,\text{s}^{-1}\,\text{GeV}^{-1}],$$

Contemporary X-ray data were available from OSO-8 and HEAO-1 for both COS-B observations (Worrall *et al.* 1979) and may be represented by a single power-law photon spectrum. The spectral index at high energies is $\alpha = 1.41 \pm 0.02$, whereas the index in the range 13–120 keV is $\alpha = 1.67 \pm 0.14$. A comparison of the X-ray spectral data with those of COS-B is shown in figure 14.

A significant change in the slope of the spectrum is apparent, when going from the X- to the γ-ray region, as well as that which exists around 30 keV in the HEAO-A2 and HEAO-A4 data. The data suggest that the peak luminosity of 3C 273 could be expected in the region of 2 MeV.

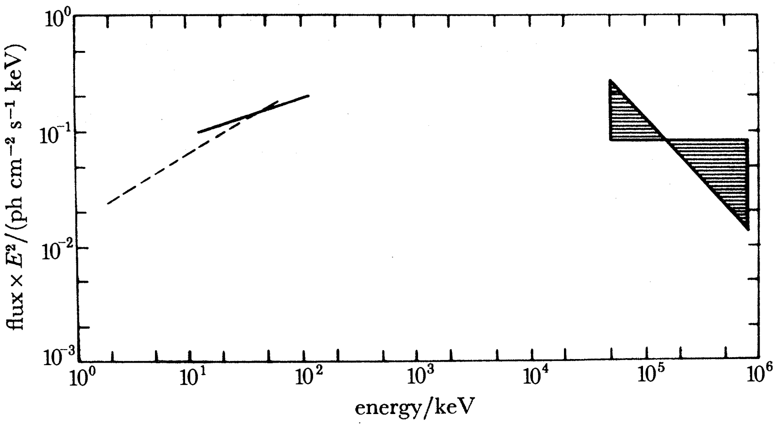

FIGURE 14. The X-ray and γ-ray spectra of the quasar 3C273. (After Bignami *et al.* 1981.)

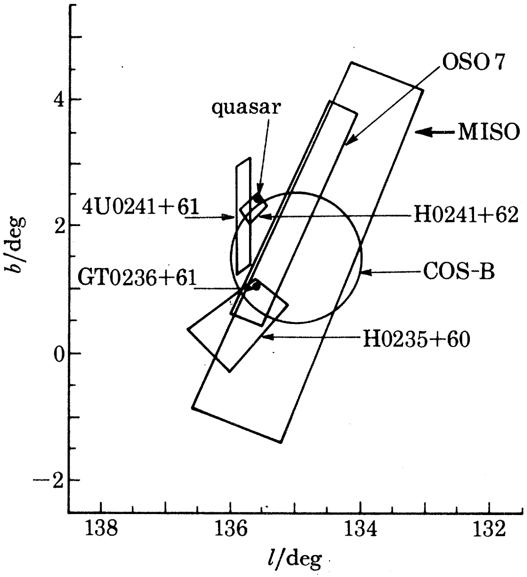

FIGURE 15. The positional error boxes associated with X- and γ-ray observations of the region of the sky around 2CG135+01.

No variability in the flux from 3C 273 was noticed at γ-ray energies in the COS-B data. However, the X-ray source is well known for its variability (Worral *et al.* 1979, Primini *et al.* 1979). Bradt *et al.* (1979) measured a threefold increase in the X-ray flux over six months. Recent data from the High Resolution Imager on the Einstein Observatory (Elvis *et al.* 1980) have brought new evidence for the short-term variability of the kiloelectronvolt emission from 3C 273. A flux change of about 10% was observed on a timescale of the order of 5×10^4 s. If it is assumed that this timescale indicates the dimensions of the X-ray source, then the photon–photon optical depth for the 50–800 MeV γ-rays is typically of the order $10 \lesssim \tau \lesssim 30$. This implies that, in the absence of any beaming of the radiation, the COS-B source cannot coincide with the variable Einstein Observatory source associated with the nucleus of the quasar.

The closest known quasar is QSO 0241 + 622. Although the original error box of the COS-B source CG135 + 1 (Hermsen *et al.* 1977) contained this quasar, subsequent analysis has shown this positional coincidence to be marginal (Pollock *et al.* 1981). The MISO low energy γ-ray telescope has detected a source of low energy γ-ray emission from this region of the sky (Perotti *et al.* 1980, della Ventura *et al.* 1979). Both the COS-B and the MISO error boxes overlap the galactic radio source GT0236 + 61 as indicated in figure 15. The spectral measurements from both telescopes shown in figure 16 provide a further indication that the excess emissions relate to the same astronomical object.

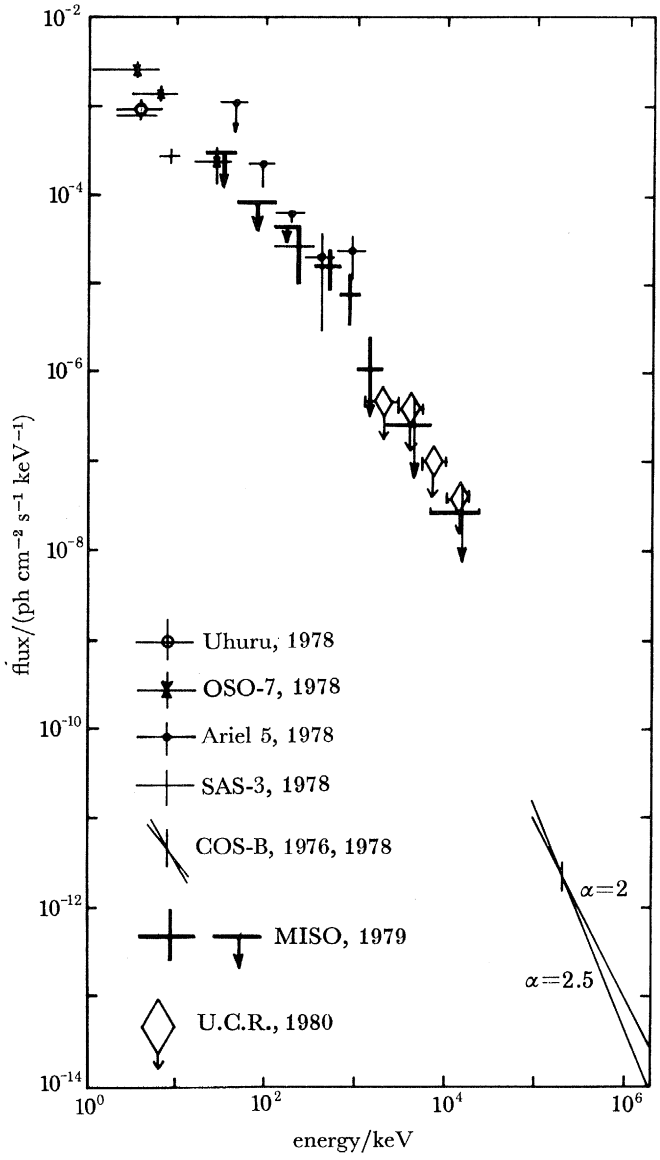

FIGURE 16. The spectrum of the γ-ray source CG135 + 1.

(*b*) *BL Lacertae objects*

Since the identification of the radio source VR09222/1 (MacLeod & Andrew 1968) with the variable 'star' BL Lacertae (Schmitt 1968) many similar objects referred to as BL Lacertae objects have been found. We are uncertain of the properties of the class (Weiler & Johnston 1980) and they may well represent an intermediate transition phase between quasars and radio galaxies. In the X-ray range, not much information is available on BL Lac objects. Six have been detected so far with luminosities in the range 10^{44}–10^{45} erg s^{-1} (2–6 keV). Detailed spectra, as shown in figures 17 and 18 have been measured over the range 2–50 keV for the objects MKN 501 and MKN 421 (Schwartz *et al.* 1978*a*, 1978*b*; Mushotzky *et al.* 1978*c*). Extrapolation to the 100 MeV region predicts intensities roughly ten times the upper limits obtained from spark chamber measurements (Bignami *et al.* 1979) and we must conclude that the spectra of BL Lac objects steepen appreciably above X-ray wavelengths. Markaryan 421 varies above 1 keV: Mushotzky *et al.* (1978*c*) observed a sixfold change in six months in the energy range 2–10 keV; Ricketts *et al.* (1976) observed a 20-fold increase in ten days in the energy range 2–18 keV. It would appear that the X-ray emission is correlated with the optically brightest BL Lac objects. These may therefore also be the closest ones. Schwartz *et al.* (1979), summarized the X-ray properties of BL Lac objects. As in the similar case of X-ray emitting Seyfert galaxies the fact that emission is of the same order of magnitude as, or greater than, the optical variations, suggests that the same basic energy source generates the emission in both wavebands. None of these objects has yet been detected as a γ-ray source.

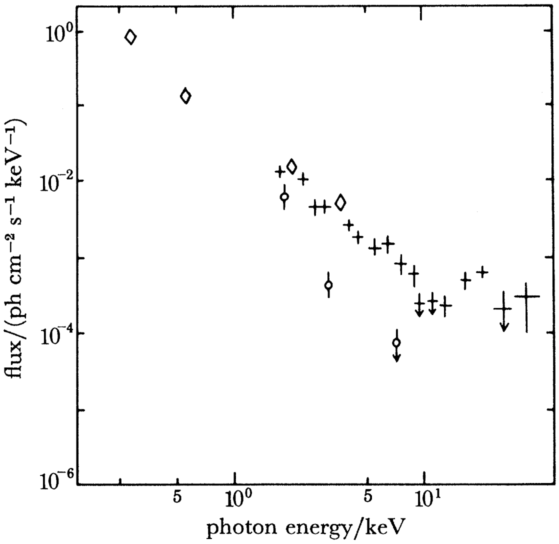

FIGURE 17. The X-ray spectrum of MKN 421.

(*c*) *Other active galaxies*

NGC 5128 (Centaurus A) is the closest radio galaxy and one of the brightest radio sources. It has huge lobes separated by *ca.* 5°, collinear with minor lobes separated by *ca.* 4′ on either side of the galaxy. Microwave studies indicate that the nucleus is compact (Kellerman 1974). It was one of the first extragalactic objects to be identified as an X-ray source (Bowyer *et al.* 1970), and has been extensively studied at X-ray wavelengths during the past decade (Stark *et al.* 1976, Winkler & White 1975, Mushotzky *et al.* 1976, Mushotzky *et al.* 1978*b*). The observations provide evidence for marked variability in the intensity and also suggest changes in the spectral index. The data indicate that the X-ray intensity of Cen-A has varied by at least a factor of five from 1971 to 1976. Winkler & White (1975) report a twofold increase in about six days in 1973.

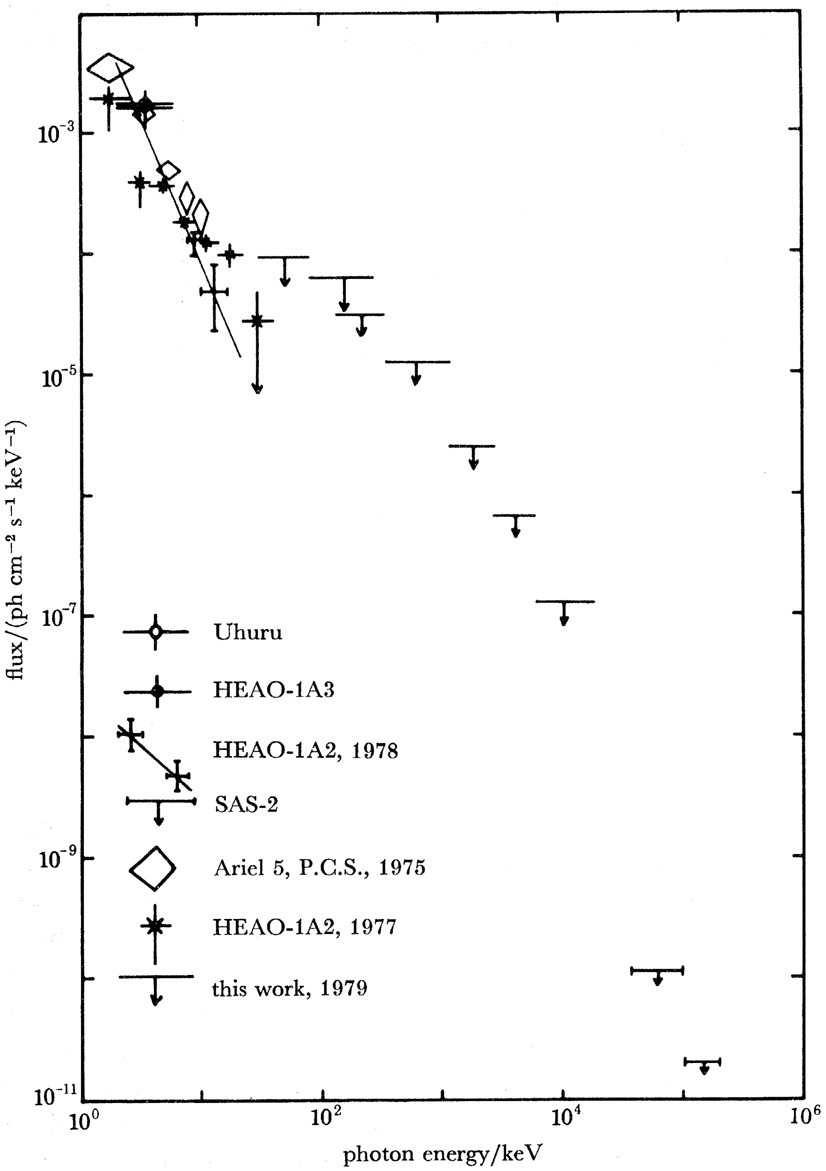

FIGURE 18. The X-ray spectrum of MKN 501.

The data of Mushotzky *et al.* (1978*b*) indicate that the flux can also decrease on short timescales. Simultaneous 10.7 GHz measurements in 1976 (Beall *et al.* 1978), indicate that the radio and X-ray fluxes probably vary in phase. The amplitude of the X-ray flux variation (*ca.* 40 %), however, was considerably greater than the radio changes (*ca.* 18 %). The existence of a flux decrease on a short timescale implies the existence of loss mechanisms that can operate on this timescale. The total energy emitted in the 4–60 keV band is of the order 10^{45} erg if a distance of 5 Mpc to Cen A is assumed.

Cen A was observed by Hall *et al.* (1976) at energies in the 30 keV–12 MeV region. They found a good fit to the continuum radiation of the form $(0.86 \pm 0.17)\ E^{-1.90 \pm 0.04}$ ph cm^{-2} s^{-1} keV^{-1}. Gamma-ray lines were also detected for the first time from an extragalactic source. Two nuclear γ-ray lines were detected above the continuum level. One at 1.6 MeV was detected at the 3.3σ level, equivalent to $(3.4 \pm 1.0) \times 10^{-3}$ ph cm^{-2} s^{-1}. The other feature was at 4.5 MeV also at the 3.3σ level and its intensity corresponded to a flux of $(9.9 \pm 3.0) \times 10^{-4}$ ph cm^{-2} s.

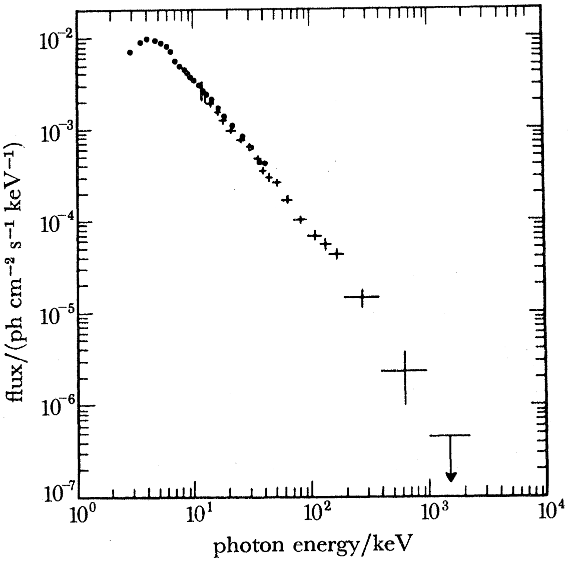

FIGURE 19. The X-ray and γ-ray spectra of the radio galaxy Centaurus A (NGC 5128) during January and July 1978. ●, HEAO A2; +, HEAO A4.

There was also a feature around 3 MeV at the 2.25σ level. There was some evidence that the 1.6 MeV line had some intrinsic line broadening. The authors concluded that the data from a series of drift scans were consistent with emission by NGC 5178, which was most likely from the galactic nucleus itself. The continuum luminosity of the galaxy was found to be 4.7×10^{43} erg s^{-1} (0.33–12.25 MeV). Since the same team failed to detect γ-radiation during an earlier observation in 1968 we may conclude that the source is variable at γ-ray wavelengths. The luminosity of the 1.6 MeV line corresponds to a level of 2.6×10^{43} erg s^{-1}. It is interesting to note that the 4.5 MeV line (*ca.* 2.2×10^{43} erg s^{-1}) is tantalizingly close to the carbon line at 4.43 MeV and may well represent evidence of $^{12}C^*$ radiation. We are even more uncertain of the origin of the broad 1.6 MeV line and it may be generated by the blending of several nuclear γ-ray lines. If it is a single, broadened, feature then the parent nuclei should be classified as low energy cosmic rays. $^{20}N_e^*$ for example, would have characteristic energies of 22 MeV nucleon^{-1}.

Cen A has also been studied in the range 80–2300 keV with the A4 instrument on HEAO during January and July 1978 (Baity *et al.* 1980). They found that the continuum emission was well represented by a power law $E^{-1.6}$ which breaks to $E^{-2.0}$ at 140 keV. No evidence was found in their data for the line emission that had been reported previously. The 2σ upper limits for the 1.6 MeV feature was 2.2×10^{-4} ph cm^{-2} s^{-1} which is one-tenth the earlier measurement. During the period of each observation there was no indication of variability on the timescale of days or less but there was a significant (*ca.* 50%) increase in intensity between the two observations which were separated by six months. The value given for the luminosity of Cen A in the range 140–2300 keV was 1.1×10^{43} erg s^{-1} with the assumption that the distance to the radio galaxy is 4.4 Mpc. The results obtained by the HEAO A4 experiment are included in figure 19.

Although γ-ray emission is not seen in the 30–10^3 MeV region of the spectrum by either SAS-2 or COS-B, a strong indication of very high energy ($E \geqslant 3 \times 10^{11}$ eV) γ-ray emission has been found (Grindlay *et al.* 1975).

4. Sources of power in X- and γ-active galactic nuclei

Gamma-ray observations of at least three active galaxies, NGC 4151 a nearby Seyfert Galaxy, 3C273 a quasar, and NGC 5128 (Cen A) a nearby giant radio galaxy, should provide important information with which to test theories relating to the origin of the activity of such objects. It is surprising that such a large proportion of the luminous output of these active galaxies is in the γ-ray region of the spectrum. Apart from this γ-ray emission, active galaxies appear to have other common properties. For example, their spectra in the X-ray region are relatively flat, and the high energy (above 30 MeV) flux limits indicate a significant steepening of the spectrum in the low energy γ-ray range. For NGC 4151 this steepening has actually been measured. Generally speaking, all classes of active nuclei are variable over a wide range of photon energies with significant changes in the emitted flux taking place on a timescale of days or even less. The γ-ray sources in particular may generally be characterized by low X-ray absorption, strong optical emission line spectra and a compact millimetre component. These observations give a strong impetus to the construction of models in which these phenomena are related. It is entirely possible that the same basic metabolism may be common to all types of active galaxy.

(*a*) *Compton models*

Several models have been proposed to explain the emission from active galaxies up to γ-ray energies. It is generally assumed that the sychrotron mechanism is responsible for a significant fraction of the intense radio, i.r. and optical fluxes that are generally observed from the nuclei of active galaxies. This in turn suggests that the inverse Compton process may be active in the production of X- and γ-ray emission from these objects. The Compton process may be further subdivided into two categories: (*a*) in scattering of the energetic electrons from ambient 'thermal' photons (I.C.S.) and (*b*) the scattering of the energetic electrons from their own synchrotron photons (S.S.C.).

Schlikeiser (1980*a*, 1980*b*) proposed a two-component model in which ultraviolet and soft X-ray photons ($E < 20$ keV) are scattered by relativistic electrons via the inverse Compton process into the hard X-ray and γ-ray regions. A flat X-ray spectrum would be produced if there were a low energy cut-off in the relativistic electron distribution. The observed breaks in the γ-ray energy spectrum are naturally explained by higher-order effects in the Klein–Nishina cross section. Alternatively, one may consider scattering from thermal i.r. photons (Bergeron & Salpeter 1973), but for the more rapidly varying source, such as NGC 4151, it is unlikely that the X- and γ-ray fluxes are generated in this way since the infrared emission region would be too large to allow X-ray variability of less than about a year.

In a synchrotron self-Compton model the X- and γ-ray emissions arise from the Compton scattering of the photons produced by synchrotron emission by the electrons that produced them. In the simplest case of this model, the synchrotron and Compton-synchrotron intensities, the common spectral slope and the size of the source region may be used to estimate the spectral intensity of the electron source. The size of the source region may be estimated from the time variability or from the observed self-absorption. The mean value of the magnetic field B and the lifetime of the electrons against synchrotron (T_s) and Compton (T_C) losses may also be estimated (Jones *et al.* 1974). For sources in which this mechanism is operative, one should look for regions of the spectrum with the same slope, for example the i.r./optical and X/γ-ray in NGC 4151, and the keV X-ray and 100 MeV γ-ray emission in 3C273. Several other active nuclei have been discussed in the light of these models and many of the source parameters estimated (Mushotzky 1977, Bergeron & Salpeter 1973). In those sources where the Compton energy density is much greater than that due to the synchrotron radiation, multiple Compton scattering becomes significant and γ-ray emission is expected to be dominant. In fact, if such a mechanism is operative in 3C273, the electrons would have to lose more than 90% of their energy through the self-Compton radiation. Generally we would expect the Compton flux variations to be correlated with the synchrotron variations but with a larger amplitude. The variations will depend on the precise source injection mechanisms for the electron spectrum and the electron density. However, one may expect a twofold or more change at the higher energy end of the spectrum for a typical 10–20% variation in the synchrotron emission. The lifetime of the injected electrons against synchrotron and Compton losses has been used to describe the observed flaring in the nuclei of many active galaxies. The injection of a large number of relativistic particles would result in the production of one X-ray flare (Mushotzky 1977) for NGC 4151, for example. The timescale of the flux increase may be related to the filling of the emission region by relativistic particles, and the timescale for decay is that of the electron losses due to photon production. This type of model can be easily tested by correlated studies of the intensity and spectral changes at the different wavelengths involved.

In this general class of S.S.C. models, the cut-offs are necessarily highly variable and may be used as a signature of this mechanism. The observed break between the X-ray and the γ-ray regions of the spectrum may be attributed either to a corresponding break in the original electron energy spectrum or to γ-ray absorption by pair production in collisions between γ-ray and X-ray photons. This latter hypothesis has difficulty in explaining the results of NGC 4151 for which the break occurs well above 500 keV. The first hypothesis of a break in the electron spectrum has to explain a sudden change in the spectral index by at least 3.4 to account for the transition from the hard E^{-1} X-ray spectrum to the steep $E^{-2.7}$ γ-ray spectrum. This dramatic change cannot stem from ionization and radiation energy loss of relativistic electrons.

(*b*) *Massive black hole models*

None of the Compton or S.S.C. models attempt to explain the source of the electrons that generate the photon fluxes. The luminosity and time variations may, however, be used to gain a deeper insight into the basic energy source.

Variations in the continuum emission provide a constraint on the maximum dimensions of the radiative source in the nucleus of any particular galaxy. We may also obtain a lower limit for the size of the source by considering the amount of energy emitted during the active phase. For example, for Seyfert galaxies the lifetime should be at least 10^8 years if all spiral galaxies go through an active phase (Weedman 1977). Thus, when the galaxy is in the active phase the total energy radiated is given by

$$L_T = \epsilon Mc^2.$$

We may therefore estimate the mass involved in the active region from this relation, where ϵ is efficiency of the process.

The Swartzchild radius r_s associated with this mass is a lower limit on the size of the source region. For a spherically symmetric source, the minimum timescale for variability is then given by

$$\Delta t = r_s/c = GL_T/\epsilon c^2.$$

If the luminosity is taken as the X-ray luminosity of the source then the observed X-ray variability may be compared with this estimate for Δt for a sample of active galaxies (table 2).

Table 2

galaxy	observed time-scale Δt/s	luminosity L/(erg s^{-1})	energy range/keV	predicted time-scale Δt/s
NGC 4151	3×10^5	5×10^{42}	2–10	1
	700	1×10^{45}	2–10^4	200
MCG 8-11-11	3×10^6	9×10^{43}	2–10	20
MK 421	1×10^5	1×10^{45}	2–80	200

For NGC 4151 the predicted value of Δt is very close to the shortest observed X-ray variations and the total luminosity (X and γ) is just compatible with that expected from a massive black hole. A similar exercise may be done for quasars. Their higher luminosity ($L \approx 10^{47}$ erg s^{-1} for 3C273), implies that the minimum timescale for variations would be of the order of days. Recent observations of 3C273 with the High Resolution Imager on the Einstein Observatory (Elvis *et al.* 1980) have brought new evidence for short-term variability in the kiloelectronvolt energy range. In particular, on December 4, 1978 a flux variation of 10% was observed on a timescale of the order of 50000 s and was confined to a region 12″ in radius centred on the quasar. If X- and γ-ray variability on a timescale close to Δt is generally observed in active galactic nuclei, one is forced to conclude that such objects are powered by massive black holes located in their central regions.

One theory, which uses a massive Kerr black hole in the production of X- and γ-ray photons is the Penrose photon-production process (Leiter & Kafatos 1978, Kafatos & Leiter 1979, Kafatos 1980, Leiter 1980). High energy photons, falling towards the event horizon, are blue-shifted in the local non-rotating frame of reference by factors of between ten and 30. Two processes will readily take place so long as an ample supply of γ-rays enter the ergosphere: they are Penrose pair-production (P.p.p.) and Penrose–Compton scattering (P.C.s.). In the (P.p.p.) process a blue-shifted γ-ray, with energy in the range tens of megaelectronvolts to gigaelectronvolts, scatters off an in-falling proton, thus injecting it and producing pairs that subsequently escape with energies that may be as high as about $4m_pc^2$. In the P.C.s. process, a blue-shifted γ-ray, having an energy less than a few megaelectronvolts, scatters off an in-falling electron and escapes with an energy that may be as high as $4m_ec^2$. The emission is restricted within a cone perpendicular to the axis of rotation of the black hole.

Predictions for the spectrum of γ-rays produced by the P.C.s. process have been made by Piran & Shaham (1977*a*, *b*). A very important characteristic of both the Penrose photoproduction processes is that there is a natural cut-off in the emission. The energy of this cut-off is strongly controlled by the mass of the particle involved. For Seyfert galaxies, in which steepening of the spectra between X-ray and γ-ray energies may be a general characteristic (Bignami *et al.* 1979), and NGC 4151 in particular (Perotti *et al.* 1979), Penrose–Compton scattering could be the dominant production process. For the radio galaxy Centaurus A and the quasar 3C273 for which no similar break in the spectrum is observed near 3 MeV (Hall *et al.* 1976, Bignami *et al.* 1981), the emission may arise from Penrose pair-production. If this is so, a break in the spectrum would be expected at gigaelectronvolt energies.

The mass of the central black hole in NGC 4151 has been estimated to be about $10^8 M_\odot$ while that in 3C273 could be of the order of $10^{10} M_\odot$. The Penrose process drains energy away from the rotating black hole and therefore the process has a finite lifetime. Although it is not entirely clear how the combined effects of accretion and Penrose emission will affect the spin as a function of time, a rough value for the lifetime for the Penrose processes may be obtained if we assume that a large proportion of the luminous power is derived from the rotational energy of the black hole. Variability is associated fundamentally with this theory since Penrose processes can only take place during periods of instability when the inner ergosphere is filled with plasma. For example, Leiter (1980) predicts that NGC 4151 will emit γ-ray transients ($E_\gamma \leqslant 3$ MeV) lasting for times of the order $2.2\ M_\odot$ hours separated by 'off' periods of the order of days. This interpretation might explain the apparent variability in the recent low energy γ-ray data for this source. Longer observations from long-duration balloon flights or satellite-borne experiments are needed to establish more firmly that the P.C.s. mechanism is operative in this Seyfert galaxy. It is important to note that the P.C.s. predicts a specific cut-off (below 3 MeV) which is essentially constant in time and should be the same for each burst. This distinguishes the P.C.s. γ-ray burst mechanism from other possible mechanisms, such as the Compton scattering model suggested by Pinkau (1979), in which the spectrum and its cut-off could vary widely in time, for different bursts. Again further observations are needed to test this unique P.C.s. prediction.

5. Conclusions

All of the observations of extragalactic objects at γ-ray wavelengths indicate that a break must occur in the spectrum at low γ-ray energies. Furthermore, they all exhibit variability on timescales down to the order of days. This variability tends to be more rapid at higher energies and indicates that the source region is small; one may assume that the high energy photons are directly related to the source of energy in active galaxies. Theories for the origin of X- and γ-ray emission from these objects provide an explanation for the breaks in the spectra, and further observations may determine which of the proposed mechanisms is dominant. For example, the Penrose–Compton scattering process requires a break in the spectrum at about 3 MeV, and while observations of NGC 4151 have provided evidence for this, other observations of the low energy γ-ray spectra from active galaxies are needed to confirm it.

If active galaxies have a lifetime of the order of 10^8 years and exhibit intensity variations of the order of days, then it follows that the central nucleus is both very massive ($m > 10^8 M_\odot$) and very compact; probably a massive black hole. Alternatively, if the break in the spectrum arises because of photon–photon interactions between γ-rays and the local intense X-ray flux, assumed to have the observed spectrum, then one is again driven to the same conclusion, namely that the central object is both massive and compact. The wide 'variety' of extragalactic objects in fact appear to have very similar overall characteristics when viewed in the X- and γ-ray regions of the spectrum. In view of the limited nature of the currently available data these apparent similarities may disappear when a more complete and detailed catalogue of extragalactic objects is available.

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Discussion

J. L. CULHANE (*Mullard Space Science Laboratory, Department of Physics and Astronomy, University College London, U.K.*). You said that active galaxy X-ray sources do not exhibit low energy cut-offs in their spectra. In fact, of the three sources you discussed (3C 273, NGC 4151 and NGC 5128) the latter two are strongly cut off with $10^{23} \lesssim N_{\mathrm{H}} \lesssim 3\times10^{23}\ \mathrm{cm^{-2}}$. This absorption, seen to vary by Ariel 5 for NGC 4151, is probably due to the gas clouds in the 'broad line' regions surrounding the active galactic nuclei. Perhaps this material has a role in γ-ray production? It would be interesting to look for time differences between X-ray and γ-ray flux changes and changes in N_{H}.